Ultrasonic Non-Destructive Diagnostics of HV Insulators

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***Abstract*- The paper presents non-destructive ultrasonic method for investigations of long-rod insulators, operated on overhead power lines and stations. It was established correlation between the degree of C 120 porcelain material degradation and the parameters of ultrasonic wave propagation and attenuation. As example of application of the method there were presented ultrasonic examinations of two groups of insulators – 15 line and 49 station post. On the basis of the measurements advancement of ageing degradation of the material and the quality of the tested insulators were ascertained.**

I. INTRODUCTION

The acoustic method is based on the dependence of the parameters of waves' propagation on the properties of the medium, where the waves propagate. In case of a solid body they depend on the elastic properties of the material, as well as on its structural composition. The ultrasonic method has been widely applied in flaw detection. Detecting the discontinuities of the medium is performed by introducing a wave beam into investigated material and then recording its reflection from the boundary. Among possible applications of ultrasonic method, very important is elastometry. On the basis of experimentally determined values of the velocities of longitudinal – c_L and transversal – c_T ultrasonic waves, as well as known material density ρ, it is possible to obtain Young's modulus E and Poisson's ratio ν values [1]:

$$E = \rho c_T^2 (3c_L^2 - 4c_T^2)/(c_L^2 - c_T^2) \qquad (1)$$

$$\nu = (c_L^2 - 2c_T^2)/2(c_L^2 - c_T^2) \qquad (2)$$

One of the most important factors, proving the correctness of the ceramic material structure, is porosity. Porosity contents and its parameters have significant influence on mechanical and electrical properties of the insulator porcelain. This effect can be described by lowering of the elasticity modulus. The porosity changes the elastic Young's modulus of the material, and as a consequence decreases the longitudinal velocity c_L as well as transversal c_T. It was proven that velocities of ultrasonic waves' propagation decrease linearly with the growth of porosity contents [2].

An additional significant ultrasonic parameter, which above all allows evaluating the extent of the aging processes in ceramic material, is attenuation. Lowering and deformation of the signal amplitudes are a result of energy dissipation. This effect is due to the existence of numerous structural heterogeneities, such as micro-cracks, frequently spaced pores, larger crystalline phase precipitations, as well as areas where mechanical stresses appear and especially if the network of cracks is present. By measuring of the decrease of signal amplitudes, after passing through the insulator diameter in subsequent measured points, and by observing the amplitude distortion, the homogeneity, as well as the quality and degree of aging of the porcelain at the core, can be evaluated. Due to complicated geometry of insulator rod and parameters of the ceramic material, measurements of amplitude attenuation coefficient are often difficult and not reliable. The attenuation of porcelain body can be assessed using indirect method. In such procedure amplitude of the signal passing through the rod diameter is registered. This value can be considered as inversely proportional to the attenuation of the medium.

II. MEASURING SET-UP

The ultrasonic tests of the insulators were performed using specially constructed set-up. Its construction enabled measurements in laboratory and also on-site. Weight and overall dimensions of the apparatus were small and it was equipped with accumulators. Its technical parameters were adopted for testing the elements made of material with high degree of structural degradation. The basic components of the set-up are the transmitting – receiving module, digital oscilloscope and a set of ultrasonic piezoelectric transducers. The sending – receiving module was designed and constructed in the Institute of Fundamental Technological Research of PAS [3].

III. EXAMINATION OF LINE INSULATORS

The authors investigated the group of 15 LP 75/17 line insulators, made of C 120 kind porcelain in 1970s, which were in operation for about 30 years period. Results of the ultrasonic

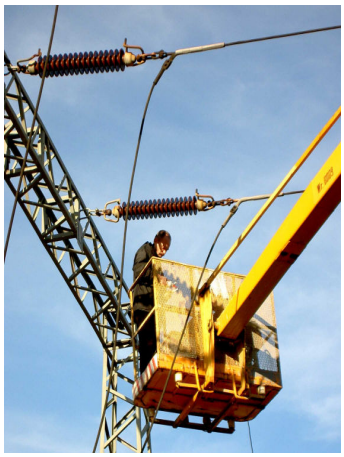

Figure 1. View of the researcher preparing to test of strain insulators LP 75/17 type on the gate support.

measurements obtained for tested insulators in place of operation were collected in TABLE I [4]. In the table are put values of the velocity of longitudinal wave propagation c_L, signal amplitude A and calculated on the basis of equation (1) elastic Young modulus E. Density of the porcelain, determined using material of damaged insulators of the same type, was equal to $\rho = 2.41$ g/cm^3. Due to geometrical restrictions, being the consequence of the insulators' rod shape, the measurement of the amplitude attenuation coefficient was not possible. The damping of ceramic body was determined using an indirect method, by registering of the signal amplitude in volts. The measured value was inversely proportional to the medium attenuation.

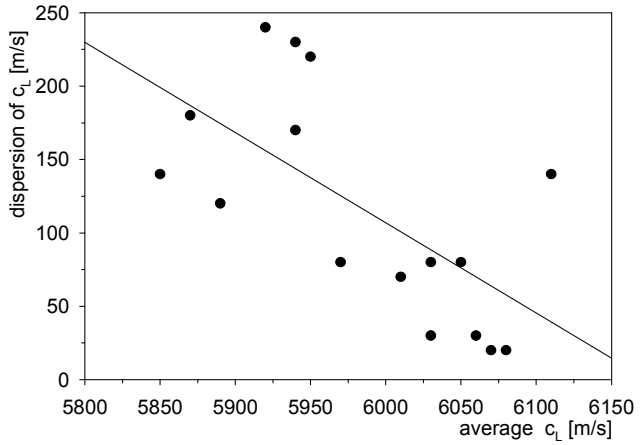

Figure 2. Dependence of dispersion of velocity of longitudinal wave propagation c_L versus average value of c_L for the group of tested insulators.

TABLE I
RESULTS OF THE ULTRASONIC MEASUREMENTS OF THE GROUP OF DOMESTIC INSULATORS LP 75/17 AFTER ABOUT 30-YEARS OPERATION PERIOD.

Ordinal Number	Measured Parameter	Average Value	Range of Value	Relative Dispersion
1	c_L [m/s]	5980	5790÷6180	6.5 %
2	A [V]	3.3	2.1÷4.5	73 %
3	E [GPa]	74	69÷79	13.5 %

Relative dispersion = 100 %·(value$_{max}$-value$_{min}$)/value$_{average}$

The procedure of ultrasonic measurements included tests done at consecutive points between the sheds, as well as next to both fixing devices of each insulator. On Figure 1 there is presented testing of insulators directly in operation. On Figure 2 is shown dependence - range of c_L values measured along insulator rod versus average value of c_L for each insulator.

Dispersion of c_L velocity for individual insulators was situated in the range from 20 to 240 m/s. Average value was equal to 120 m/s. Results indicated considerable diversity of the range of material inhomogeneity along insulator rod in tested group of objects. Dispersion was generally higher for insulators showing lower average c_L value of the material (Figure 2). Elastic module and mechanical strength of these elements were poorer as well. Significant dispersion of material parameters (TABLE I) and its properties are consequence of porcelain constitution and technological factors. Advanced aging processes amplified effect of dispersion. The presence of meaningful defects was not detected in tested group of insulators. Elements containing such faults must have already been broken.

Tested insulators LP 75/17 were characterized by generally not high quality and homogeneity of ceramic material. They were made of aluminous porcelain C 120 kind. Constitution of the material was typical for technology used in 1970s. After about 30 years' period of operation porcelain structure underwent advanced aging degradation processes – Figure 3

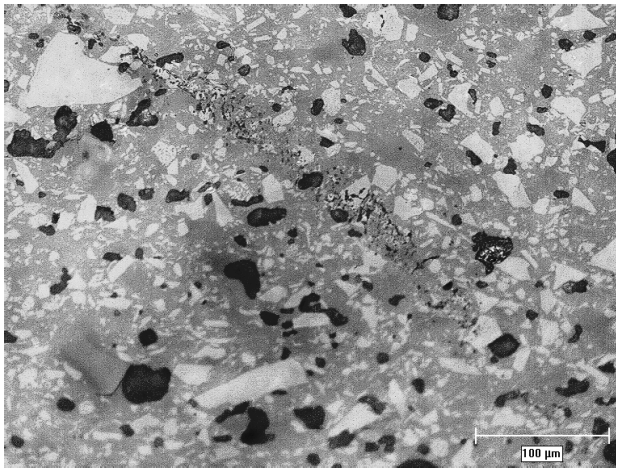

Figure 3. Image of the material structure of LP 75/17 insulator rod from 1973, magnification 200x. High contents of quartz (partly crushed out) – 37 % and band of microcracks are visible.

First of all, it was a consequence of high and diversified contents of quartz phase in the material - between 20 and 37 %, average value 29 %. Quartz frequently occurred as bigger grains (over 30 µm). This phase was the main source of internal stresses, initiation and growth of cracks in the ceramic body. Existence of all sorts of defects or inhomogeneities intensifies aging process of degradation, especially in case of strain insulators' material. Operational stresses have significant influence on intensity of degradation effect. Different material properties in the areas of rod and sheds give evidence of this

observable fact. External loads result in considerable enlarging of degradation effects in a rod of line insulators.

IV. Diagnostics Of Station Post Insulators

Besides line insulators, the ultrasonic investigations were also carried out on the group of 56 post insulators, operated on industrial power engineering stations 110/6 kV [3,5]. The insulators SWZPAK-110 type, made in Poland in 1972-1976, underwent ultrasonic measurements. These insulators have been in exploitation for nearly 30 years. Measurements of 49 insulators were performed directly on the isolating switches, one was after breakdown. Further 6 objects came from the station reserve and were taken from the storehouse.

Considering geometrical restrictions, length of ultrasonic signal path and relatively high attenuation of the insulator material, it was necessary to perform series of comparative structural and acoustic tests. This allowed determining correlation between the degree of defectiveness in the ceramic body and measured signal amplitude. The high amplitude values – over 2.2 V, indicate low degree of material aging and lack of structural defects. The values below 1 V are not only the result of the advanced aging processes, but most of all, reveal the presence of faults such as cracks, delaminations or areas characterized by released texture and high, no uniformly distributed porosity in the ceramic body. The most common range of amplitudes - from 1.0 to about 2 V – indicates the lack of significant defects of the material, but at the same time the presence of the aging processes at various stages of advancement. This dependence is confirmed by relatively low values of ultrasonic wave velocities. Results of tests of 56 post insulators are presented in TABLE II.

TABLE II
Results of ultrasonic measurements of the group of post insulators SWZPAK-110 after about 30-years' operation period.

Ordinal Number	Measured Parameter	Average Value	Range of Value	Relative Dispersion
1	c_L [m/s]	5730	5360÷6010	11.3 %
2	A [V]	1.7	0.3÷3.5	188 %
3	E [GPa]	64.5	57÷71	21.7 %

Relative dispersion = 100 %·($value_{max}$-$value_{min}$)/$value_{average}$

It should be emphasized that in the whole group of the tested insulators high dispersion of the material properties was observed. This comes not only from the diversified degree of the material aging process advancement, but most of all from the differences in initial parameters of the electrotechnical porcelain. However, a clear-cut assessment of the tested insulators is difficult, it can be stated that parameters of the material are low and significantly worse than in case of line insulators – TABLE I.

On the basis of measurements there was ascertained similar advancement of ageing processes in the material of exploited insulators and non-operated ones, taken from station reserve. This means that external – operational stresses have low influence on ageing effect in the material of post insulators. Due to this fact, parameters of the material in the area of rod and sheds of insulators are approximately the same.

On the basis of the results of measurements of ultrasonic waves' propagation and their attenuation for a group of 56 SWZPAK-110 insulators from the years 1972-1976, the following facts were ascertained:

- 8 insulators (14.3 %) contained defects, which create high probability of breakdown, one of them underwent breakage;
- 11 insulators (19.6 %) had defects, which cause increased risk of breakdown;
- 37 insulators (66.1 %) contained no detectable defects.

Typical structure of the material of exploited post insulator was presented on Figure 4.

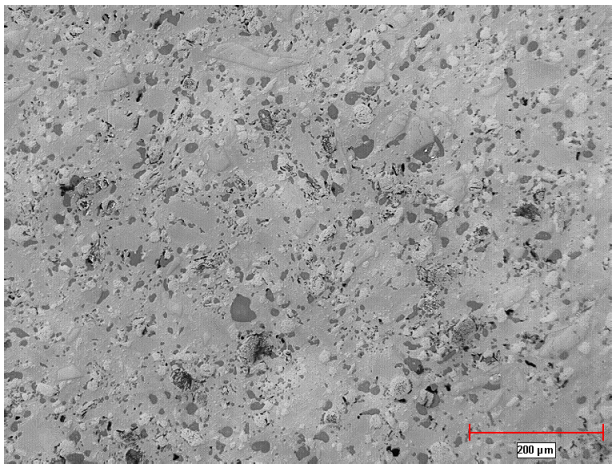

Figure 4. Typical image of the material structure of the insulator SWZPAK-110 rod, produced in the middle of 1970s, magnification 200x. Effect of medium advanced ageing processes - numerous microcracks and crushed out grains of quartz are visible.

The phase analysis of broken SWZPAK-110 insulator material allowed formulating the conclusion that the material corresponds to typical electrotechnical porcelain of C 120 kind, of the older type. Material is characterized by an acceptable homogeneity. The average composition of the porcelain consists of about 24% quartz, over 32% mullite, where 8.5% has the form of needles. The glassy matrix content is about 40%. The presence of corundum crystals in the ceramic body was not detected. The average porosity varies from typical value equal to 3 % to 9 % in defected areas. An important material feature that was ascertained in all areas of the tested insulator is its advanced aging process. This process reveals itself by a large amount of micro-cracks, which are usually adjacent to numerous quartz grains. The latter usually also show cracks. Significant part of grains was completely separated from matrix and was crushed out during polished sections preparation – Figure 4.

V. Conclusions

Tested insulators - line and station post - were characterized by generally not high quality and homogeneity of ceramic

material. They were made of aluminous porcelain C 120 type. Constitution of the material was typical for technology used in 1970s. After about 30 years' period of operation porcelain structure underwent advanced aging degradation processes. The most advanced appeared in rods of line insulators. In their case, operational stresses played essential role. For post insulators an external loading had only small influence on aging processes advancement. Reserve post insulators, taken to examination from storehouse, showed unexpectedly similar degree of material degradation as in case of operated insulators. Crucial influence on aging of post insulators' material have internal stresses.

Parameters of the material of line insulators are considerable better than post ones. There were not found any detectable defects in tested line insulators. Material parameters of both examined groups of insulators exhibit high differentiation. This is the consequence of not constant technological conditions and composition of raw material in 1970s. Aging processes strengthened dispersion of porcelain parameters.

For line insulators, it was stated that if the average velocity of ultrasonic waves – measured along insulator rod – was lower, when dispersion of this parameter was higher. This concerns also elastic module values and mechanical strength of insulator material.

Obtained results of ultrasonic and microscopic examinations lead to conclusion that after about 30 years' period of operation, insulators made of C 120 kind porcelain, should be withdrawn from exploitation.

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